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PRECAST CONCRETE PAVEMENTS

by

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Final Report

PRECAST CONCRETE PAVEME

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This report reviewed published literature on precast concrete pavements and found that precast concrete pavements have had some limited application in airfields, roads, and storage areas. This review of past experience and an analytical study of precast slabs concluded that existing design and construction techniques can be adapted for use with precast concrete pavements, but more work is needed to develop effective and easily constructed load transfer designs for slab joints. Precast concrete does not offer any advantage for
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20. ABSTRACT (Continued)

conventional pavements due to its high cost and surface roughness, but it may find applications for special problems such as construction in adverse weather, subgrade settlement, temporary pavements that need to be relocated, and military operations.

PREFACE

This investigation was conducted by the Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES) during the period November 1978-September 1980. The study was sponsored by the Office, Chief of Engineers, U. S. Army, under Project No. 4A161102AT22, Task Area AO, Work Unit 005, "Analysis of Precast Articulated Pavement System Units."

This study was conducted under the general supervision of Dr. W. F. Marcuson III, Chief, GL, and Mr. A. H. Joseph, Chief, Pavement Systems Division (PSD), GL. The study was conducted by Mr. R. S. Rollings and Dr. Yu T. Chou, PSD.

Commanders and Directors of WES during this investigation and preparation and publication of this report were COL John L. Cannon, CE, COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. Frederick R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
feet per pound (force)	1.355818	joules
inches	0.0254	metres
kips	4.448222	kilonewtons
miles (U. S. statute)	1.609347	kilometres
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic inch	27,679.90	kilograms per cubic metre
square feet	0.09290304	square metres
square inches	0.00064516	square metres
square yards	0.8361274	square metres
tons (short, 2000 pounds)	907.1847	kilograms

PRECAST CONCRETE PAVEMENTS

PART I: INTRODUCTION

Background

1. The use of precast concrete structural members is a widely applied, well-established, economical construction technique. Concrete columns, beams, panels, piles, pipes, railroad ties, and other elements for a variety of structures are cast at permanent factories or temporary casting yards, transported to the construction site, and then assembled. Advantages of precasting are as follows: generally good quality control, economical mass production, rapid construction, reduced congestion at the side, and rapid availability of the structure for use. A previous study by the U. S. Army Engineer Waterways Experiment Station (WES) (McDonald and Liu 1978) found that precasting could be applied by U. S. Army Engineers in a theater of operations for construction of structures such as bridges and field fortifications.

2. Despite the widespread use of precasting in the construction industry, the application of the technique to pavements has been very limited. Because a concrete pavement consists of a very large number of identical slabs, mass production of precast pavement slabs could be economical. More rapid construction, construction in adverse weather, improved use of materials, and reduced cost are potential benefits of precasting concrete pavements.

Purpose and Scope

3. This report will evaluate the potential application of precasting concrete pavements. The history of precast concrete pavements will be reviewed; design, manufacturing, construction, and potential applications will be evaluated. This study is a literature review and analytical study of precast concrete slabs that carry their load through slab bending, as a conventional rigid pavement. Precast concrete block

pavements, composed of approximately brick-sized modular units, behave in a manner similar to that of flexible pavements and will not be considered in this report. Engineer Technical Letter 1110-3-310 discusses precast concrete block pavements and includes a report prepared by the WES containing details of design, specifications, construction, and performance (Office, Chief of Engineers, 1979).

PART II: LITERATURE REVIEW

Soviet Union

4. The first concrete airfields in the Soviet Union were constructed in 1931-1932 of precast, unreinforced concrete hexagons 4.1-ft-long* sides and 3.9- to 5.5-in. thicknesses. Heavier aircraft introduced after World War II required larger hexagons 4.9 ft long and 5.5 to 8.7 in. thick. The unreinforced hexagons tended to rock and spall; and when modern concrete placing equipment became available after 1950, new pavements were built of rectangular, cast-in-place, reinforced concrete slabs (Glushkov and Rayev-Bogoslovskii 1970, Rayev-Bogoslovskii et al. 1961).

5. In the Soviet Union, where the precast concrete industry is extensively developed, precast, prestressed concrete slabs remain an acceptable construction material for airfields. By 1970, precast slabs were considered acceptable for airfields subjected to twin-tandem gear loads of 121 kips and tire pressures of 142 psi and single-wheel gear loads up to 66 kips and tire pressures of 142 psi (Glushkov and Rayev-Bogoslovskii 1970). Precast slabs were not recommended for pavements subject to the heaviest twin-tandem design gear loads of 154 kips and tire pressures of 142 psi. The use of precast slabs on airfields was reported to be increasing yearly, particularly when nonuniform swelling or settlement was a problem, rapid construction was required, conventional concrete construction was inefficient due to project geometry or size, strengthening of existing pavements was needed, or when construction took place at temperatures below freezing (Glushkov and Rayev-Bogoslovskii 1970, Rayev-Bogoslovskii et al. 1961). One Soviet source also suggested precast slabs as an efficient pavement repair material (Mikhno 1974).

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is found on page 3.

Precast road pavements

6. Precast slabs have been used extensively for roads as well as for airfields in the Soviet Union. By 1962, over 180 miles of temporary roads such as forest roads were constructed with precast slabs, and a 10-year evaluation of a precast road showed favorable results (Maidel and Timofeev 1962). Further experiences with precast roads in Moscow, under heavy industrial traffic in the Donbass, on the Kiev-Odessa Highway, and in other projects were reported in the Soviet technical literature with favorable results (Glushkov and Rayev-Bogoslovskii 1970; Birger and Klopovskii 1961; Mikhovich, Tarasenko, and Tolmachev 1961; Timofeev and Leutskii 1961; Dubrovin et al. 1962; Smolka 1963; and Stepuro et al. 1964). Glushkov and Rayev-Bogoslovskii (1970) stated that precast road construction had not yet proven economical. In contrast to this conclusion, it was reported that an estimated 95,000-120,000 sq yd of precast pavements were placed in Moscow between 1968 and 1974 and that amount was increasing (Mednikov, Malchanov, and Gorodelskii 1974).

Types of precast slabs

7. Biaxially prestressed slabs are preferred for Soviet precast pavements, particularly for those subjected to heavy aircraft loads, because they use material more efficiently than conventional plain and reinforced slabs. Actual size and reinforcing of slabs are dictated by the facilities available at the precasting plant. The designs of the six slabs shown in Table 1 are approved by the Soviet government for general manufacture (Glushkov and Rayev-Bogoslovskii 1970, Rayev-Bogoslovskii et al. 1961, and Gerberg and Osipon 1962). These slabs are 5.5 in. thick, but with minor adjustments at the manufacturing plant they can vary from 4.7 to 6.3 in. thick. The PAG-IX slab is biaxially prestressed with a longitudinal prestress of 400 psi and a transverse prestress of 300 psi. The remaining slabs are prestressed only in the longitudinal direction. A number of precasting plants have reportedly mastered the manufacture of the PAG-XIV slab (Glushkov and Rayev-Bogoslovskii 1970). Precast unreinforced slabs 3.3 by 3.3 ft, reinforced and unreinforced hexagonal slabs 3.8 by 4.9 ft with 3.8-ft-long sides, and prestressed slabs varying from 5.7 to 9.8 ft wide by 19.7 ft

long are used in road construction (Glushkov and Rayev-Bogoslovskii 1970, Mednikov, Malchanov, and Gorodelskii 1974).

Design and construction

8. One recommended design procedure for Soviet concrete airfield pavements compares a calculated slab bending moment to an allowable moment for the slab (Glushkov and Rayev-Bogoslovskii 1970). The design is an iterative procedure to bring the bending moment to within 5 percent of the allowable moment. The bending moment is calculated for a single wheel load multiplied by dynamic and overload factors, assuming an elastic plate on a Winkler foundation of independent springs. Superposition is used to account for additional wheel loads for multiwheeled gears. The moments are redistributed to account for uniaxial prestress if needed, and the largest moment is then multiplied by a transfer coefficient to convert it to a bending moment at the edge of the slab. The allowable moment is calculated from the cross-sectional geometry, flexural strength of the concrete, and reinforcing and prestress levels. Load repetition and temperature effects are handled by a variable coefficient, and the flexible strength of the concrete is multiplied by a factor of 0.7 to account for variability in strength (Glushkov and Rayev-Bogoslovskii 1970). Hexagonal slabs have generally been designed on the assumption of a center load on a circular slab, but an approximate solution for hexagonal slabs with edge loadings has also been presented (Mednikov, Malchanov, and Gorodelskii 1974). The load capacity of precast slabs is varied by changing the foundation strength, since the slab thickness, strength, and reinforcing are already standardized.

9. Soviet precast slabs have been placed both with and without load transfer devices at the joints between slabs. The PAG-1X slab contains additional reinforcement at the edges and corners of the slab, and there is no load transfer across the joint between slabs. The other PAG slabs have two brackets along the short, transverse side of the slab, and brackets between adjacent slabs are welded together. Joints every 59 to 66 ft are left unwelded to allow temperature-induced movements. Other jointing methods reported in use include keyed joints, epoxy-filled joints, and sand and cement grout-filled joints (Mednikov,

Malchanov, and Gorodelskii 1974). One Soviet investigator reported that severe rocking of hexagonal slabs occurred under the traffic of a 9700-lb axle load unless a stabilized base was used (Mednikov, Malchanov, and Gorodelskii 1974). No load transfer devices were used with these slabs.

10. In the Soviet Union, a 1.6- to 2.4-in.-thick layer of sand or sand cement is used as a leveling course for the construction of precast pavement (Gerberg and Osipon 1962). The slabs are placed with a crane and kept aligned with string lines. The slab is then lifted and the impression is visually checked and corrected for high and low spots. This method may require three to five tries before an acceptable fit is obtained. An alternative method is to vibrate the slabs into place with a large vibrator. Two other less common methods include blowing sand under a suspended slab or mudjacking a slab to obtain the desired elevation. Placement rates are reported to be as high as 950 sq yd per shift per crane. Construction tolerances are a maximum joint width of 0.6 in. and a maximum differential elevation of 0.2 in. between adjacent slabs.

United States

Prestressed concrete missile mat

11. In 1956, the Ohio River Division Laboratory, U. S. Army Engineer Division, Ohio River, investigated a precast, prestressed sectional mat to prevent erosion and dust from missile firings (Mellinger 1956). This mat was to be capable of being placed by military labor, withstanding 90,000-lb thrust of the missile, and supporting traffic of missile launchers with wheel loads of 25,000 lb at a 40- to 55-psi tire pressure. Figure 1 shows the beam section developed to meet these requirements. The concrete used low-weight sintered shale aggregate and high early-strength portland cement that obtained a 28-day compressive strength of 5800 psi. The individual beams were 12 in. wide, 18 ft long, 5.5 in. thick, and weighed 550 lb. This was light enough to be handled by a team of eight men. Stirrups were used to reinforce the ribs. Pretensioned, prestressed cables along the length of the beam were stressed to 6000 lb, which provided a prestress in the concrete of 1200 psi after

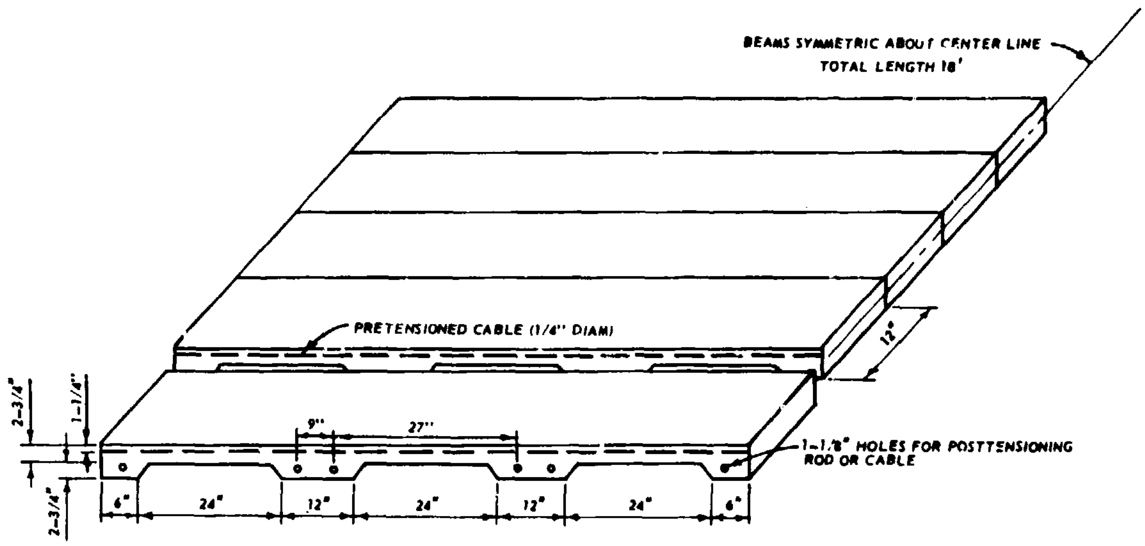


Figure 1. Precast, prestressed concrete missile mat

prestress losses. Both rods and cables were used successfully to post-tension the individual beams together transversely and build monolithic mats 18 by 20 ft and 33 by 33 ft.

12. These mats were subjected to moving wheel loads varying from 5,800 to 24,000 lb. Under traffic some spalling occurred at the edges of the beams and some of the posttensioned rods and cables lost up to 17 percent of their prestress. Strain gages on the surfaces of the beams showed that one wheel load was generally distributed over three beams. Three failures occurred in the thin plank section of the beams under 24,000-lb wheel loads. Although the sectional mat successfully withstood the missile blast tests, further study was not recommended because of the mat weight and assembly times. Further work with this concept was recommended for temporary roads or storage areas, but it was not pursued.

Prestressed highway,
Brookings, South Dakota

13. In 1968, the South Dakota Department of Highways and the Federal Highway Administration built a 24-ft-wide, 900-ft-long test section of precast, prestressed concrete slabs on U. S. Highway 14 near Brookings, South Dakota (Larson and Hang 1972). The pavement design was based

on research sponsored by the South Dakota State Department of Highways and Federal Highway Administration and conducted at the South Dakota State University (Gorsuch 1962, Kruse 1966, Jacoby 1967, and Hargett 1970). The final slab design used in construction is shown in Figure 2. These slabs were 6 ft wide, 24 ft long, and 4-1/2 in. thick. The 3/8-in.-diam longitudinal cables were prestressed to provide 400-psi prestress in the slab. A grout key as shown in Figure 2b was used on the longitudinal sides to provide load transfer between adjacent slabs. An optional connection joint (Figure 2c), used on approximately half of the slabs, was formed by widening the grout key at the slab longitudinal one-quarter and three-quarter points and welding protruding No. 3 reinforcing bars together. The concrete slabs were overlaid with asphaltic concrete, the depth of which varied from 3-1/2 in. at the road center to 1-1/2 in. at the edge to provide the required surface slope and smoothness.

14. The slabs were lifted by crane, placed on a 1/2-in.-thick sand bedding layer, and seated by a vibratory roller. Half of the slabs were placed with the long side of the slab parallel to the direction of traffic using the optional connection joints. The remaining slabs were placed with the long side perpendicular to the direction of traffic without connection joints. Tables 2 and 3 summarize the costs of this construction and compare them to conventional concrete pavement costs (Larson and Hang 1972). The South Dakota project was used as a basis or example for recommending precast construction for strengthening airport pavements (Hargett 1969) and urban pavement construction (Zuk 1972).

Precast concrete pavement repair slabs

15. The Michigan Highway Department developed a technique of pavement repair using precast concrete slabs (Jones and Iverson 1971, Transportation Research Board 1974). Eight standard designs were developed for slabs 12 ft long, varying in 2-ft increments from 6 to 12 ft wide, and either 8 or 9 in. thick (Transportation Research Board 1974). Double layers of No. 3 bars at 1-ft 6-in. spacing provided reinforcing. Weight of the slabs varied from 3.7 to 8.1 tons. Figure 3 shows the design of a 9-in. precast repair slab.

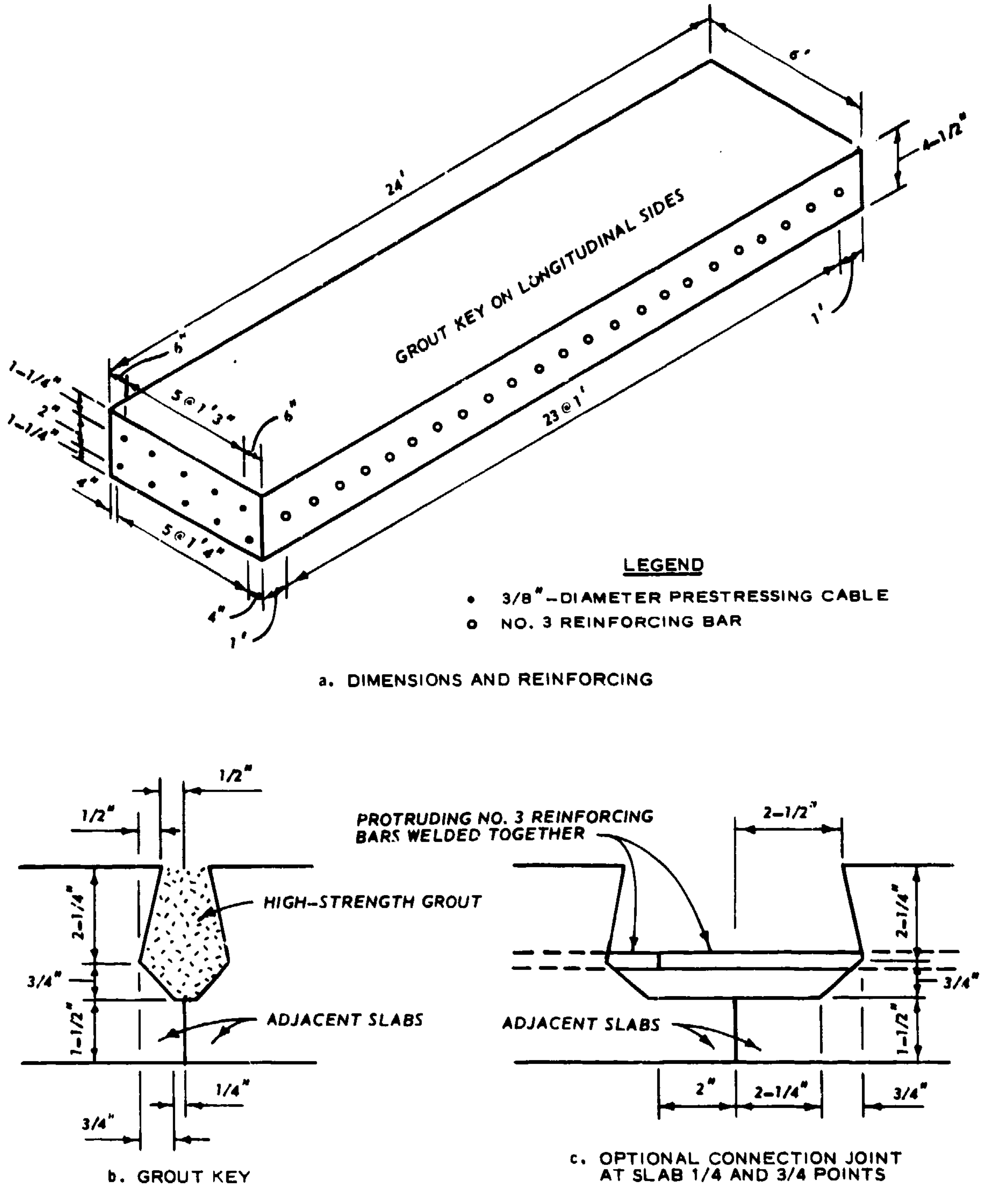
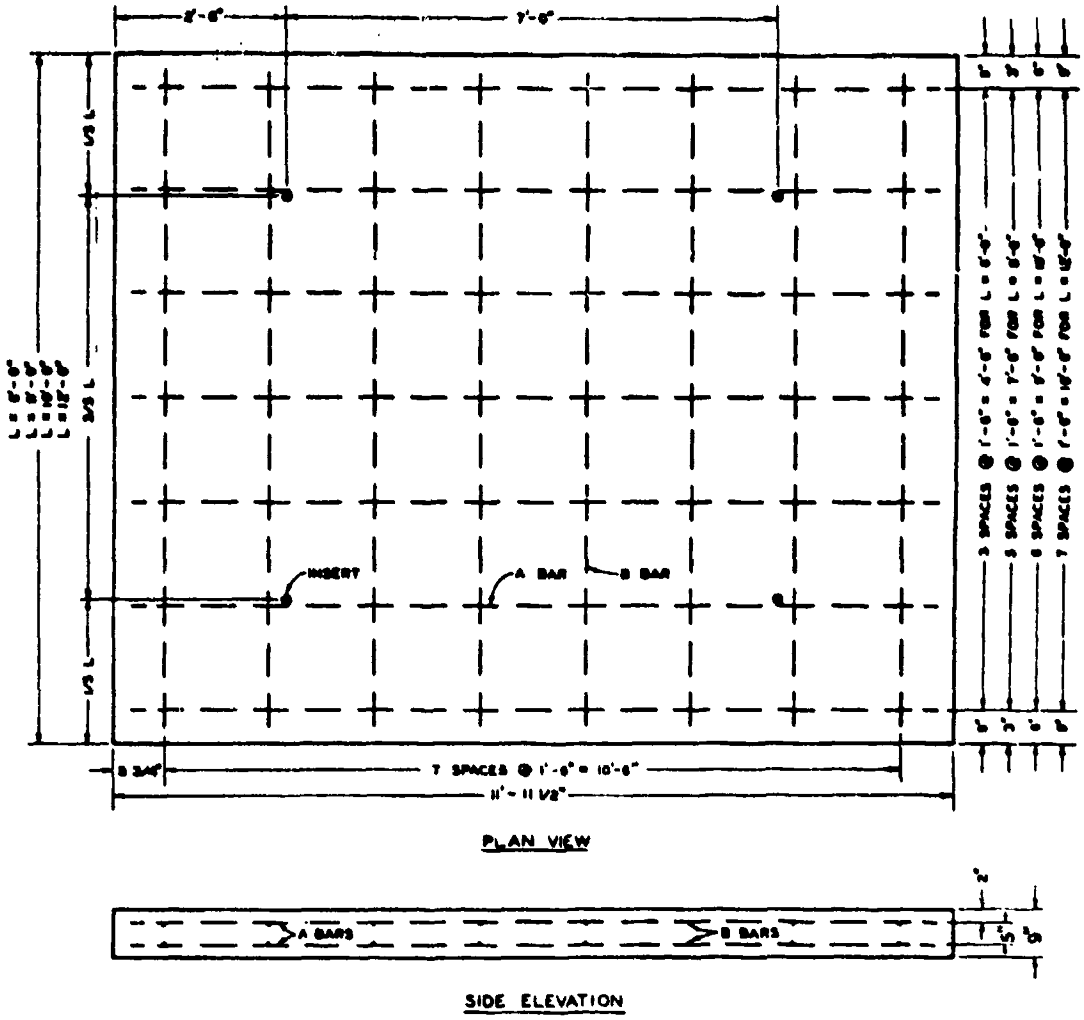


Figure 2. Final slab design for test pavement section, Brookings, South Dakota



Nominal Slab Size	Bar Designation	Bar Size	Bar Dimension	Number Required Per Slab	Concrete Required	Approximate Weight
12' x 12'	A	#3	11' - 6"	16	4.0 yd^3	16,200#
	B	#3	11' - 6"	16		
10' x 12'	A	#3	11' - 6"	14	3.3 yd^3	13,500#
	B	#3	9' - 6"	16		
8' x 12'	A	#3	11' - 6"	12	2.7 yd^3	10,800#
	B	#3	7' - 6"	16		
6' x 12'	A	#3	11' - 6"	8	2.0 yd^3	8,100#
	B	#3	5' - 6"	16		

Figure 3. Plan for 9-in. precast repair slab (from Transportation Research Board 1974)

16. In this technique, the damaged pavement is first cut out and removed. A cement-slurry mortar is placed directly on the subbase to the final elevation of the bottom of the repair slab, and then the slab is lowered into place. Transverse joints over 1/4 in. wide are sealed with bituminous filler strips, and longitudinal joints are grouted to within 2 in. of the surface. Final joint sealing with a hot-poured rubber-asphalt sealant is delayed until the slab has been open to traffic to ensure no tilting or misalignment has occurred. Reported repair times varied from 2-1/2 to 8 hr (Jones and Iverson 1971). Two alternate joint designs using dowels inserted in the existing pavement and then welded to plates cast in the repair slab and epoxy joint sealants were also tested (Jones and Iverson 1971).

17. Pavement repairs on I-29 in South Dakota, on I-95 in Virginia, and on several projects in Great Britain used partial-depth precast slabs (Transportation Research Board 1974, Byrd 1975). In this technique, which is used primarily for localized surface damages, a Klarcrete concrete cutting machine described by Byrd (1975) cuts a rectangular hole up to a maximum size of 1 ft 6 in. by 2 ft by 4 in. deep. A thin precast slab is then placed in the hole with an epoxy grout.

18. The San Diego Unified Port District replaced 116 damaged concrete slabs at San Diego's Lindbergh Field with precast reinforced concrete slabs (Engineering News Record 1981). The precast slabs were cast to match the existing slabs. Damaged slabs were removed; 6 in. of subgrade was excavated; and lean concrete was placed to the desired elevation of the bottom of the precast repair slab. The precast slab was lowered into place and seated with a 10-ton roller. Patented load transfer devices were used at the slab joints. Precasting the repair slabs allowed the airport to stay in operation without closing down for the concrete to cure. The airport pavement was strengthened by an 8-in.-thick asphaltic concrete overlay after all repairs to the existing airport pavement were complete.

Europe

19. Between 1947 and 1958, precast, prestressed concrete slabs were used for airfield construction in Europe on several occasions. Orly Airport, Paris, France, was the first airfield application of prestressed pavement, which consisted of 3.3-ft-square, 6.3-in.-thick precast slabs (Hanna et al. 1976, Harris 1956). These square slabs were posttensioned together into a unique triangular arrangement with sliding joints. A similar design was adopted for an installation in London in 1949 (Stott 1955). During load tests conducted at Orly Airport, a 224-kip load on a 32-in.-diam plate caused a 0.41-in. deflection for interior loading and a 0.45-in. deflection with the load adjacent to the sliding joint. Although the precast Orly pavement was structurally adequate, the surface was notably rough and construction was costly.*

20. In 1956, a 200- by 200-ft section of airport pavement was constructed in Finningley, England, of 30- by 9-ft by 6-in.-thick precast, prestressed slabs posttensioned in place (Hanna et al. 1976). In 1958, a 75- by 1148-ft taxiway was constructed at Melsbroek, Brussels, with 4.1- by 39-ft by 3-in.-thick prestressed, precast slabs (Hanna et al. 1976, Vandepitte 1961). These slabs, which were in the shape of parallelograms, were pretensioned. The joints were caulked with mortar, and then the slabs were posttensioned with transverse cables.

21. Container terminals require pavements with high load capacity and good durability. Often these terminals are built on fill areas and are subject to large subgrade settlements. Precast concrete slabs provided the required strength for large concentrated loads, durability, and a flexible structure that can be releveled after settlement. For these reasons they have been used for several container terminals in Europe (Patterson 1976). Steel plates have been used on the edges of these precast slabs to prevent spalling in the Netherlands and United

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* Unpublished report by Henry Aaron, 6 Sept 1955, following inspection of prestressed concrete pavements at Orly Airport, Paris, France, and Maison Blanche Airport, Algiers, Algeria (report on file at WES, Pavement Systems Division, Vicksburg, Mississippi).

Kingdom. Generally this method performs well but is costly. A project in Hamburg used slabs 6.6 to 8.2 ft square and 5.5 in. thick, and reinforced with 0.3 to 0.5 percent steel. These slabs were chamfered to prevent spalling and have given good performance for 8 years (Patterson 1976). Patterson (1976) found that precast slabs in container terminals could have elevation variations of 0.2 in. between adjacent slabs over 10 percent of a new pavement. Generally these slabs have been economical only when large settlements were a problem.

Japan

22. Six experimental pretensioned precast concrete slabs were constructed and tested in Japan (Sato, Fukute, Inukai 1981). These slabs were designed for DC-8 aircraft and were 7.5 ft wide, 32.8 ft long, and 7.9 in. thick. The slabs were pretensioned to 412 psi at the casting plant. The slabs were placed on an 0.8-in. leveling course of cement-stabilized sand covered with vinyl sheets.

23. A unique "horn joint" was developed for this precast application. A 1.5-in.-diam steel bar approximately 27.9 in. long was bent into an arc shape with a radius of 51.2 in. Arc-shaped plastic tubes were cast in the edges of the slabs at 15.8-in. spacings. This allowed the steel bars to be inserted as shown in Figure 3 and grouted to provide load transfer across the joint.

24. A steel beam was used to level adjacent slabs as shown in Figure 4. Once the slabs were leveled by tightening the bolts in the steel beam, grout was pumped through grouting holes to fill the voids under the slabs, and the leveling beam was removed. Once the steel bars in the horn joint were sawn, individual slabs could be removed and replaced with new precast, prestressed slabs.

Summary of Literature Review

25. Table 4 summarizes the variety of precast pavement dimensions, types, and uses published in the available technical literature.

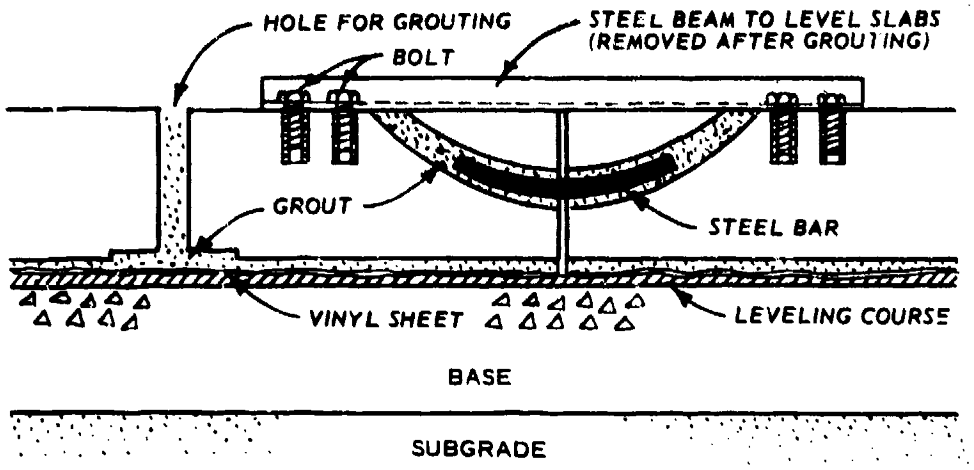


Figure 4. Japanese horn joint (after Sato, Fukute, Inukai 1981)

Most of the slabs, with several exceptions such as the Michigan or Hamburg slabs, have length to width ratios of 2 or greater and will probably behave more as one-way slabs unless adequate load transfer is provided between slabs to ensure two-way bending. Slabs have been relatively thin and have made extensive use of prestressing.

26. Most of the sources recommended use of precast slabs for special problems rather than as a direct competitor to less costly cast-in-place concrete. Typical reasons suggested for precasting have included aggregate shortage, future pavement settlement or heaving, critical speed of construction, or construction in freezing temperatures. Major problems with precast pavements have been high costs and roughness.

PART III: ANALYSIS OF PRECAST SLABS

Analytical Model

27. The effects of slab size, slab orientation, and load transfer across slab joints were evaluated with a 2-dimensional, elastic, finite element computer code, WESLIQID, developed at WES (Chou 1981a,b). This program models the concrete slab as an assembly of four node plate elements lying on a liquid subgrade. Elastic material properties are used for the concrete slab, and the modulus of subgrade reaction k is used to characterize the subgrade. Arbitrary slab shapes and varied loadings over the face of the slab can be modeled. Amount of load transfer across slab joints can be assigned to account for dowels, keys, aggregate interlock, etc.

Effect of Slab Size

28. Four slabs with dimensions in plan of 6.6 by 20 ft, 6.6 by 13 ft, 6.6 by 6.6 ft, and 3.3 by 3.3 ft, all 5.5 in. thick were analyzed to determine tensile stress in the idealized elastic material concrete and the surface deflection. These slab sizes are representative of the PAG-XIV and PAG-XV slabs with a length to width ratio of 3, the PAG-III and PAG-IV slabs with length to width ratio of 2, the smaller Hamburg slab with a ratio of 1, and the small Soviet road slab with a ratio of 1 (Table 4). This slab analysis used a concrete modulus of elasticity of 6 million psi, a Poisson's ratio of 0.15, and a subgrade modulus of 200 pci. The concrete modulus is somewhat higher than the more commonly assumed 4 million psi to account for the improved concrete quality, which should be attainable in a precasting plant. A 30,000-lb load at 105-psi contact pressure was applied at the center of the short edge of the slab. This loading is similar to that of a C-130 and of some vehicles such as the Clark 512 straddle carrier found in container handling terminals, and is also within the range of the Soviet design loadings for single-wheel gears mentioned in paragraph 5.

29. Figure 5 shows the results of this loading for these four slabs. The small slab did not bend significantly but instead settled fairly uniformly; hence, low tensile stresses and large deflections resulted. The other three slabs developed higher stresses and lower deflections. Also, for the small slab, the tensile stress nearly approaches zero at about 5 in. from the slab edge while large slabs develop negative stresses at slab edges.

30. These stresses are well beyond the elastic limits of concrete, and the slabs will crack under this load. At these stress levels even a prestressed slab will crack since the tensile stress will exceed the sum of the flexural strength of the concrete and the compressive prestress. The capacity of the slab can be increased by an increase in slab thickness as shown in Figure 6 for a PAG-XIV slab. Alternately, the subgrade support can be increased. Figure 7 shows the limited effect of increasing the subgrade modulus for a 7-in.-thick PAG-XIV slab. Analyzing the effect of strengthening the base by simply increasing the k value is generally not adequate. Current U. S. Army Corps of Engineers airfield design uses a modified pavement overlay equation for rigid pavements over stabilized bases (WES 1977, Department of the Army 1979); and a Soviet source recommends a procedure that develops an equivalent pavement thickness when designing pavements with "durable artificial bases" (Glushkov and Rayev-Bogoslovskii 1970).

31. Loads along the edge of a slab cause higher stresses than loads in the interior of the slab. The Corps of Engineers and many other pavement design agencies use the edge load as the critical design load for concrete pavements. Various devices such as dowel bars, tie bar, keyways, or aggregate interlock from sawn construction joints transfer a portion of the load from the edge of the loaded slab in a conventional pavement to the adjacent slab. The measured load transfer on airfield pavements and on test tracks has varied from 0 to a theoretical maximum of 50 percent (Ohio River Division Laboratory 1950, 1959; Grau 1979). The Corps of Engineers uses a 25 percent load transfer between adjacent slabs for design of conventional rigid pavements.

32. Figure 8 clearly shows the advantage of load transfer for a

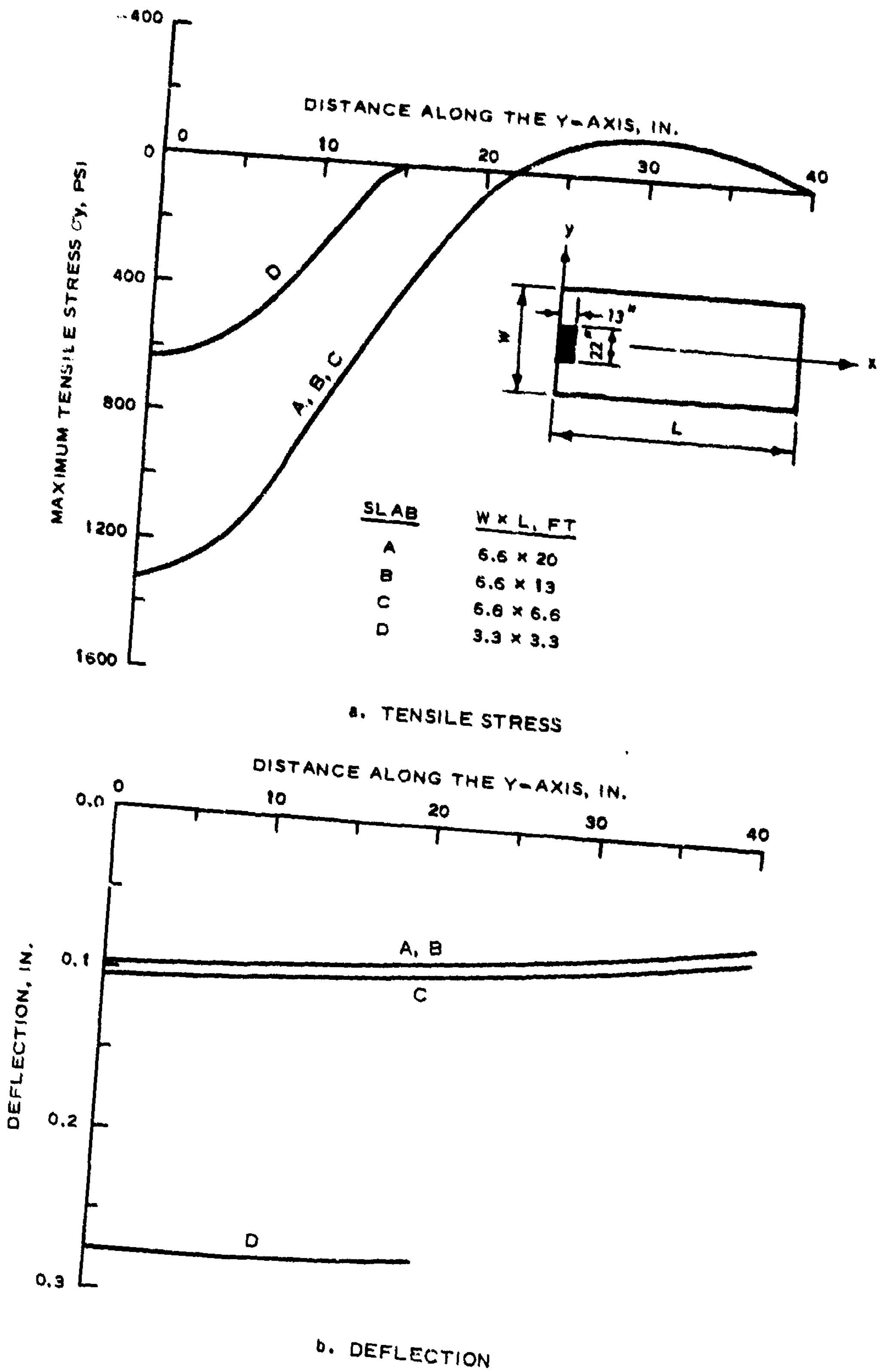
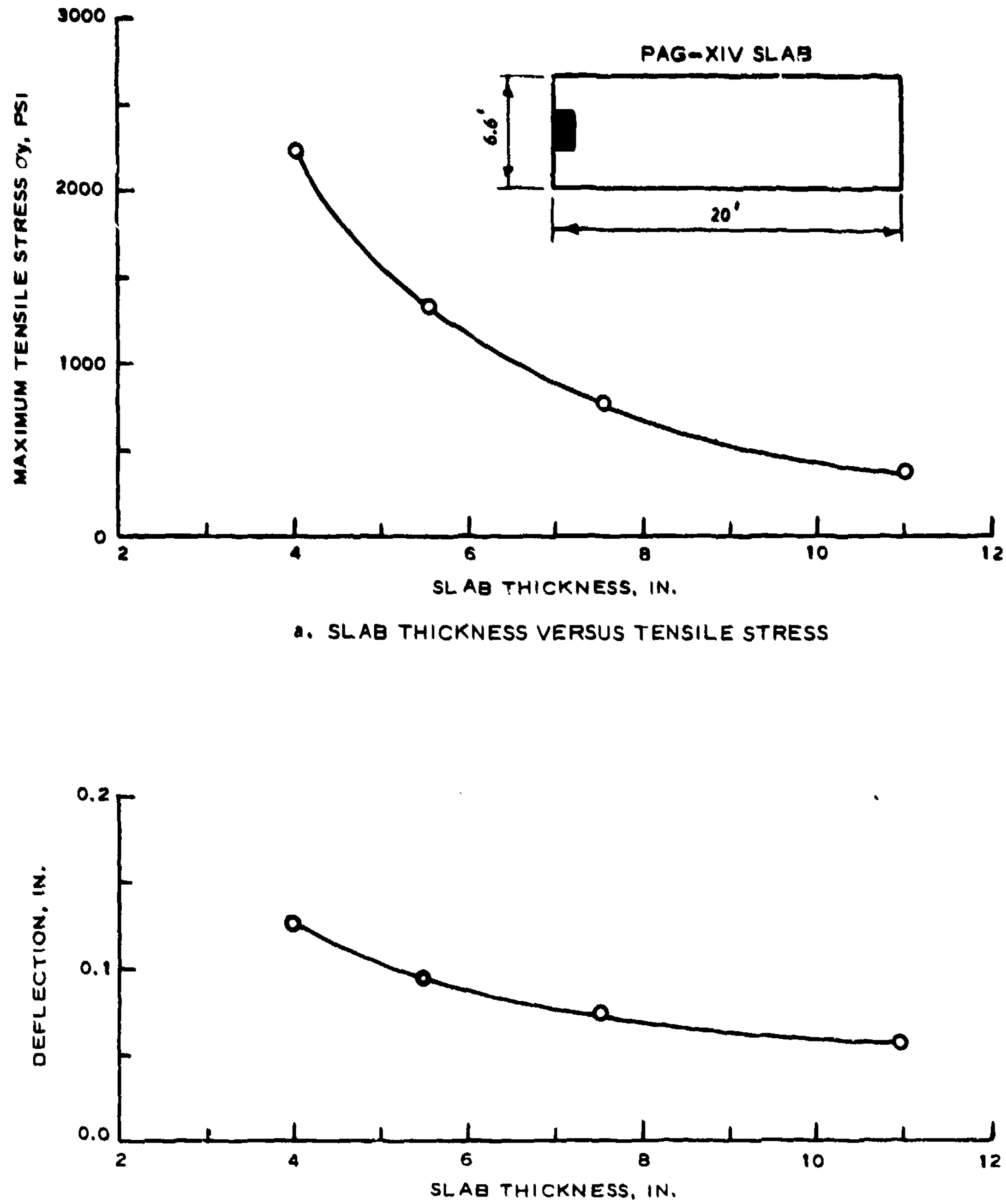


Figure 5. Effect of slab size on deflection and tensile stress, location x = 0, y = 0



a. SLAB THICKNESS VERSUS TENSILE STRESS

b. SLAB THICKNESS VERSUS DEFLECTION

Figure 6. Effect of slab thickness on tensile stress and deflection, location x = 0, y = 0

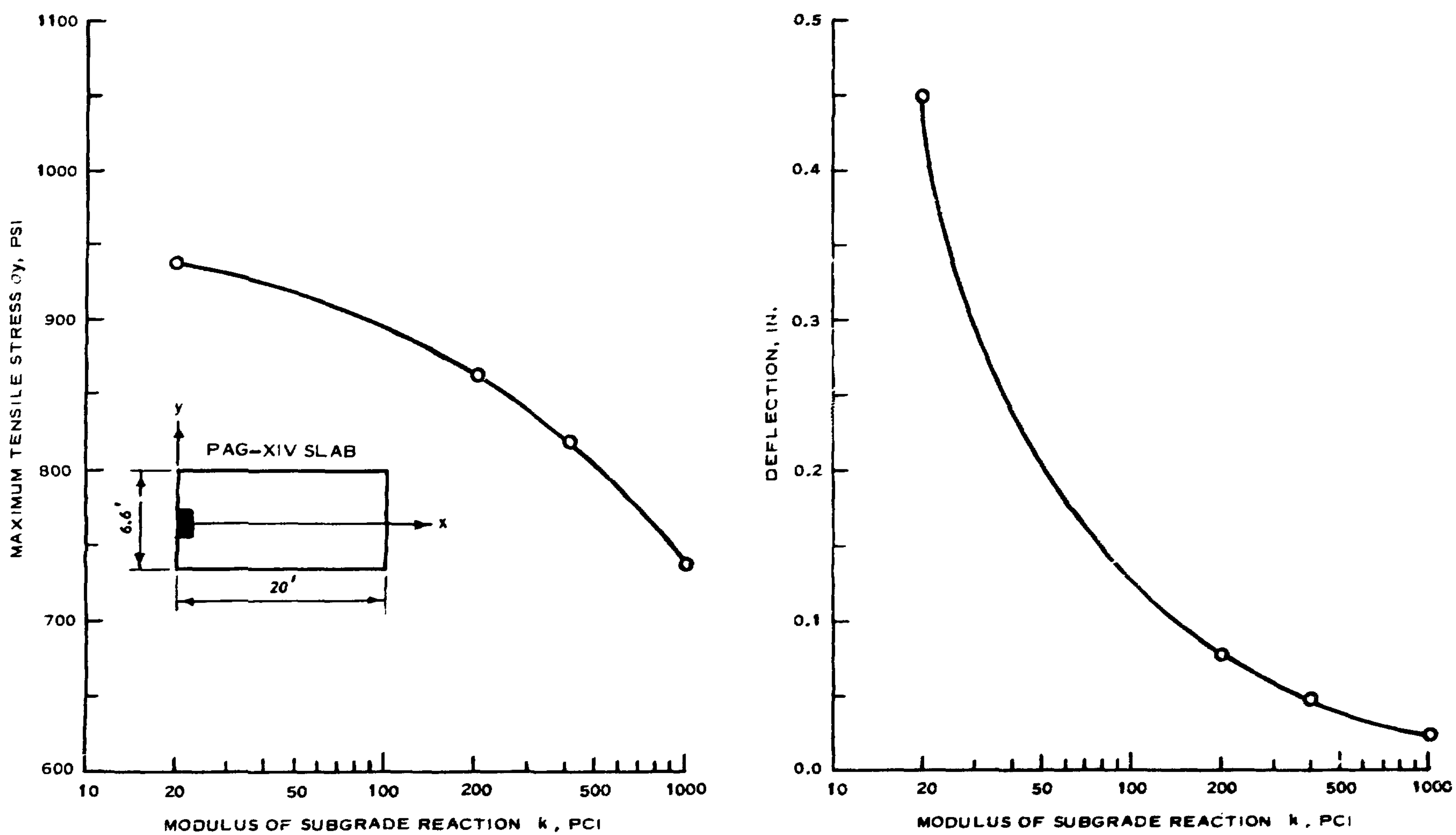


Figure 7. Effect on modulus of subgrade reaction, location x = 0, y = 0

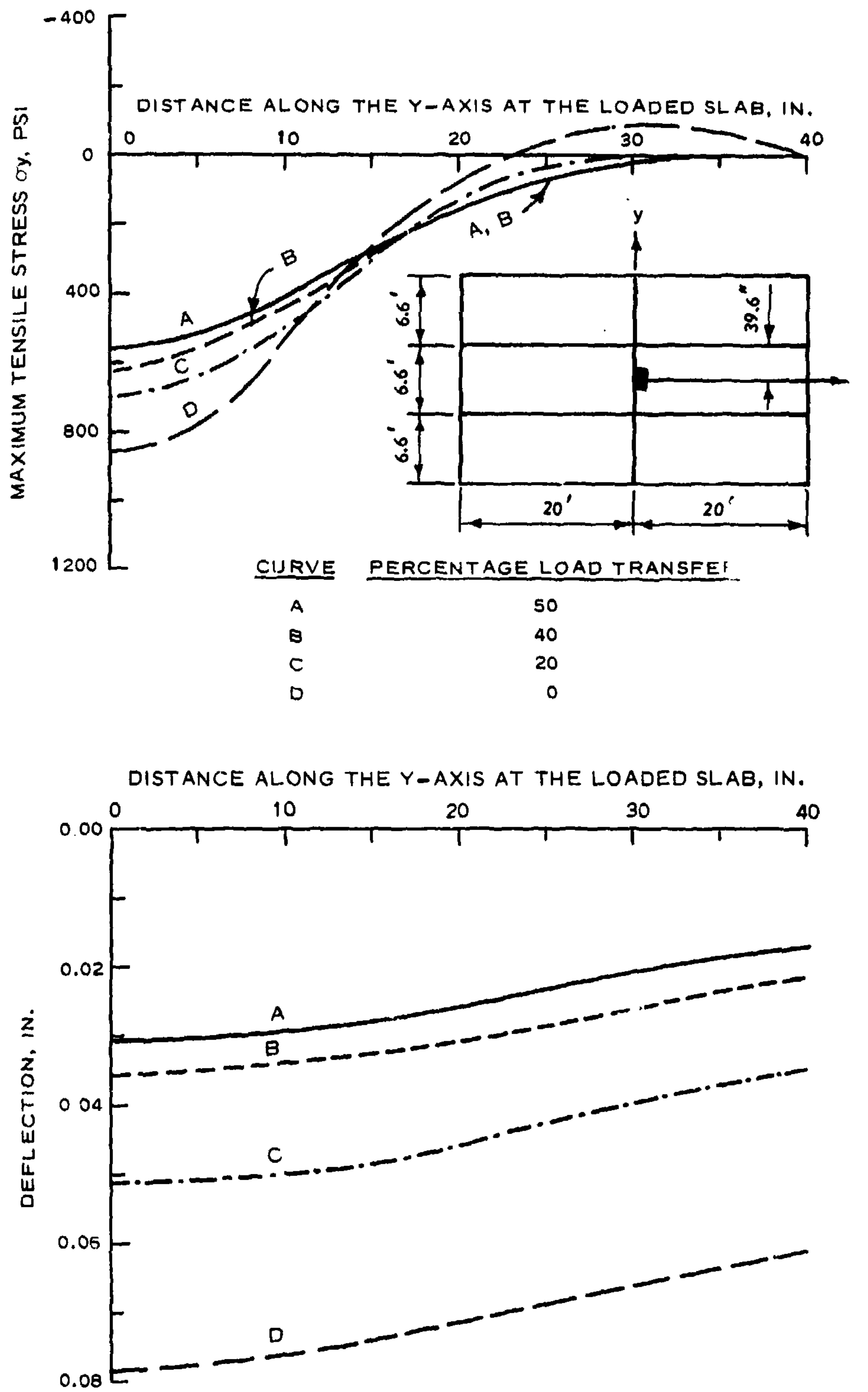


Figure 8. Effect of load transfer across slab joint, location x = 0, y = 0

7-in.-thick PAG-XIV slab. Both stresses and deflections are reduced when load transfer is achieved between adjacent slabs.

Handling Stresses

33. The most severe loading that a precast slab must resist may occur during handling after precasting or during construction rather than under traffic. Every precast slab must be designed to resist handling stresses as well as stresses from traffic loads.

34. Table 5 shows the effects of different parameters on the moments from lifting Soviet PAG-III and PAG-XIV slabs with a four-point pickup. These slabs are both 6.6 ft wide and weigh 3.1 and 4.6 tons, respectively. Since length to width ratios are 2 or greater, they may be analyzed as one-way slabs. This assumption reduces the analysis of the slab to a simply supported beam, half the width of the slab, subject to a uniform dead load. A comparison of the moments for any PAG-III and PAG-XIV slab clearly shows the effect of slab length. A pickup at one-quarter and three-quarter points reduces the moment and also changes it from positive (tension on botton of slab) to negative (tension on top).

35. This simple example illustrates the importance of carefully planning the geometry and the pickup points to reduce stresses and to control the location and type of stress (tension or compression). In conventional reinforced concrete pavements, reinforcing steel is used to keep cracks in the slab closed, not to carry tension as in structural reinforced concrete. Current Corps of Engineers practice for airfields places the reinforcing 1 in. below the midpoint of the slab (Department of the Army 1979). In this position the steel will not contribute to the flexural capacity of the slab while it is being lifted. The designer must proportion the slab and the lifting design to maintain the stresses, modified with appropriate safety factors, below the tensile strength of the concrete, or he must provide properly located reinforcing steel to carry tensile stresses after the concrete cracks.

36. The slab must be designed for impact loads from handling, for which an impact factor of 2 would be prudent. Also if the lifting cable

is at an angle to the slab surface, horizontal as well as vertical loads will be applied to the slab and must be considered. Other factors that must be considered include slabs being handled at the casting yard before the concrete develops full strength, loading from stacking during storage, and detailed design of pickup points. Gerwick (1971) and Waddell (1974) cover handling and construction of precast units in more detail. Complex loadings from storage and handling and two-way slabs (length to width ratio less than 2) may be analyzed using general-purpose computer programs such as STRUD developed by the Massachusetts Institute of Technology, NASTRAN developed by the National Aeronautics and Space Administration, or SAP developed by the University of California at Berkeley.

PART IV: DESIGN AND CONSTRUCTION

Assumptions

37. Concrete pavements are generally designed by limiting the calculated tensile stress in the bottom of the slab to an acceptable percent of the concrete flexural strength. The stress in the slab is usually calculated using the Westergaard model of a thin elastic plate on a dense liquid subgrade (Westergaard 1926, 1948). Solutions employing this model are available in the form of influence charts (Pickett and Ray 1951, Pickett et al. 1951) and a computer program (Kreger 1967). Since 1946 the Corps of Engineers has used the stress calculated from the Westergaard model for a load along the slab edge as the basic rigid pavement design parameter. A design factor, defined as the ratio of concrete flexural strength to the calculated edge stress, accounts for the effects of load repetition and temperature and moisture gradients in the concrete (Hutchinson 1966).

38. If existing Corps of Engineers design procedures are to be applied directly to precast pavements, several assumptions must be examined. The assumptions of elastic concrete properties and a single value of soil support in the form of the modulus of subgrade reaction are not theoretically rigorous but are reasonable simplifications for design of both cast-in-place and precast concrete pavements. Pavement slabs in the field warp due to temperature and moisture gradients, and the uniform slab support assumed in the design does not really exist. Although design can compensate to some extent for these discrepancies, the Corps of Engineers procedure incorporates these assumptions into the design factor developed from accelerated traffic tests and surveys of existing pavements. The potential for subsurface voids is greater for precast pavements than for coventional pavements due to grading and casting imperfections. Consequently the existing design procedures can be applied only to precast slabs that have a uniformity of support comparable to that of a cast-in-place slab. Therefore, the precast slab must be placed on a leveling course of sand or mortar to provide a

reasonable degree of subgrade support. Either a fluid mortar, vibration, or some other seating method such as described in paragraphs 10 and 14 must be used to seat the slabs securely on the leveling course. Also, results of model tests suggest that the slab dimensions should be three times the radius of relative stiffness for the slab to ensure compatibility with the assumptions of the Westergaard model (Behrmann 1964).

Pavement Types

Plain concrete

39. Plain concrete without reinforcing is the most common form of conventional rigid pavement. According to the Corps of Engineers design criteria, this type of pavement is considered to be failed when the first structural crack forms. Precast slabs of plain concrete will be relatively thick and difficult to handle because of the low tensile strength of concrete.

Steel-reinforced concrete

40. Reinforcing steel in concrete pavements does not retard the initial crack in the slab, but it does keep the crack closed tightly. The pavement continues to perform well in this state, and failure condition for the pavement is changed from cracking to spalling along the crack. This reinforcing results in a thinner slab, and the reinforcing steel can be positioned in the slab to help carry handling stresses.

Fiber-reinforced concrete

41. When short lengths of steel fiber are randomly dispersed in concrete, flexural strength, tensile strength, ductility, toughness, and dynamic strength increase. Increased flexural strength, typically 900-1300 psi for field mixes, and increased resistance to spalling are important potential advantages for fiber-reinforced concrete pavements. Also, fiber-reinforced concrete has additional load capacity after the initial crack forms; therefore, the failure criterion used with fiber-reinforced concrete pavement is the opening of a crack under traffic to a width that allows water infiltration and loss of load transfer across the crack (Parker 1979). Increased flexural strength and the upgraded

failure criterion result in a much thinner, more easily handled pavement slab for fiber-reinforced concrete. The increased dynamic strength of fiber-reinforced concrete may also provide additional protection from handling stresses.

Prestressed concrete

42. A crack forms in a prestressed concrete slab when the tensile stress on the bottom face exceeds the sum of the concrete flexural strength and the prestress compressive stresses. This cracking is the limit of elastic behavior of the slab and is the conventional point of slab failure. However, the prestressed slab will redistribute bending moments to increase the negative radial bending moment after this initial crack forms. When the load is removed, the prestress force closes the crack, allowing continued service of the slab. Failure of the prestressed slab occurs when tensile cracking develops in the surface of the slab from the negative radial bending moments. A small increase in load or load repetitions then causes a punching shear failure. The Corps uses an empirical design method based on model and accelerated traffic tests to take advantage of this inelastic slab behavior (Odom and Carlton 1974).

Lightweight aggregates

43. Lightweight aggregates may be used to make concrete with a compressive strength up to 6000 psi and a weight of 90-120 pcf. This offers a method of reducing deadweight of slabs for handling but generally at the expense of a reduced modulus of elasticity, lower tensile strength, and lower abrasion resistance.

Sample Designs

Loading

44. Sample pavement designs were prepared for four possible applications of precast concrete pavements: C-141 cargo aircraft taxiway, F-15 fighter aircraft taxiway, road, and cargo handling area. Both aircraft pavements were designed for channelized traffic; the road was designed for equivalent 18-kip axle loads; and the cargo handling area

was designed for a Hyster 620B forklift. Table 6 shows the characteristics of the loadings selected for these designs.

Design procedures

45. Designs were prepared for plain, reinforced, fiber-reinforced, and prestressed concrete for each loading. The concrete flexural strength for design was 700 psi, except for fiber-reinforced concrete that was 1100 psi. Load transfer between slabs was 25 percent whenever load transfer was assumed to exist.

46. The Corps of Engineers airfield design manual (Department of the Army 1979) was used to prepare the designs for both aircraft except for the prestressed design without load transfer. This design required a modification to the existing prestressed design method. Eleven Ohio River Division Laboratory model tests of edge loadings without load transfer found edge failure loads to be 57.3 percent of interior failure loads with a coefficient of variation of 8.4 percent.* This result was used to calculate all prestress design failure loads without load transfer. The design procedures for the 18-kip axle loads and Hyster 620B are described by Carlton (1961), Hutchinson (1966), Odom and Carlton (1974), and Parker (1979).

Design results

47. Table 7 shows the calculated slab thicknesses for the sample designs. Significantly thinner pavements can be achieved by conventional reinforcing or fiber reinforcing or by prestressing the concrete slabs. Failure to provide load transfer between slabs results in a significant increase in the slab thickness.

48. Thinner slabs will weigh less and consequently will be easier to handle and transport. Table 8 compares the weights of the different types of slabs for the C-141 design without load transfer listed in Table 7. For this specific example, the prestressed slab offers the greatest weight reduction over plain concrete with the heavily

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* Unpublished test results by Ohio River Division Laboratory conducted in 1960 as part of a project entitled "Small Scale Model Studies of Prestressed Rigid Pavements for Military Airfields." Test results now on file at WES Pavement Systems Division.

reinforced slab (0.50 percent reinforcing steel) offering the second largest reduction. These relative rankings are not constant. In the C-141 design (Table 7), the fiber-reinforced concrete slab thickness is controlled by deflection limits to protect the underlying base and subgrade. If this comparison is made for the Hyster 620B design with load transfer (Table 7), the fiber-reinforced slab will weigh 7.3 tons compared with 9.1 tons for the 0.5 percent reinforced slab.

49. A comparison of Tables 7 and 8 reveals that prestressed slabs offer the most efficient use of concrete and steel. This does not imply that prestressed slabs will always be the most practical or economical solution. For example, prestressed concrete can be used only on airfields if the subgrade modulus is 200 pci or more because of problems with large deflection of these thin pavements on weak subgrades. Either a strong base or a different type pavement must be used in these conditions. Handling stresses, which must be considered separately, probably eliminate large plain concrete slabs from consideration. Although conventional reinforced and fiber-reinforced slabs are alternatives, prestressed concrete offers clear advantages for precast pavement slabs due to efficient use of materials and relatively low final weight.

Joints

50. Table 7 shows the advantage of providing load transfer across joints. In conventional pavements this load transfer is provided through aggregate interlock on saw-cut contraction joints, dowel bars across joints, or key joints in the form of tongue and groove connections. Potential methods of providing comparable load transfer for precast slabs will be discussed in this section.

Welded joints

51. Welding two points per slab side as discussed in paragraph 9 for the Soviet PAG slabs and in paragraph 13 for the South Dakota slabs may help maintain alignment of the slabs but will not provide load transfer except possibly when the load is immediately adjacent to the welded point. A sufficient number of connection joints such as shown in

Figure 2c could be provided on all the slab sides for load transfer, but this would require a significant amount of welding in the field.

52. The preferred welded joint for reinforcing steel is a butt joint; an example is shown in Figure 9a. Due to alignment and close tolerance requirements, this would not be practical for precast pavement construction. A single-lap splice as shown in Figure 9b would be compatible with the South Dakota joint in Figure 2c. However, the eccentricity of this joint can cause distortion when loaded, which tends to split the concrete cover. The double-lap splice shown in Figure 9c is an improvement, but the number of welds is increased. Selection of the proper welding procedure depends on the actual chemical composition of the steel. A procedure that is suitable for one chemical composition can be totally unsuited for another composition of the same strength grade. It is essential that the composition of the steel to be welded be determined before a welding procedure is established. A basic rule that has been often stated is:

> Know the composition of the material that you are trying to weld. If you don't know, find out, and then adopt the most convenient and economical procedure that will give sound crack-free welds in steel of that composition.

Where reinforcing bars are to be ordered for new work, the fabricator of the bars should be told if welded splices are contemplated. Not only can the fabricator usually provide the chemical composition of the reinforcing bars, but in many cases he can supply bars that are more suited for welding.

Dowels and tie bars

53. Dowels and tie bars are sized and spaced based on satisfactory past experience rather than by theoretical analysis. Table 9 shows the Corps requirements for dowels and tie bars. Dowel bars are provided for load transfer across joints while tie bars are used to prevent separation of slabs. The Michigan road repair slabs (paragraphs 15 and 16) used 1-1/4-in. bars welded to a 3/8-in.-thick, 4-in.-wide plate cast into the precast slab (Jones and Iverson 1971). This method should provide adequate load transfer. The widely spaced, welded No. 3 bars

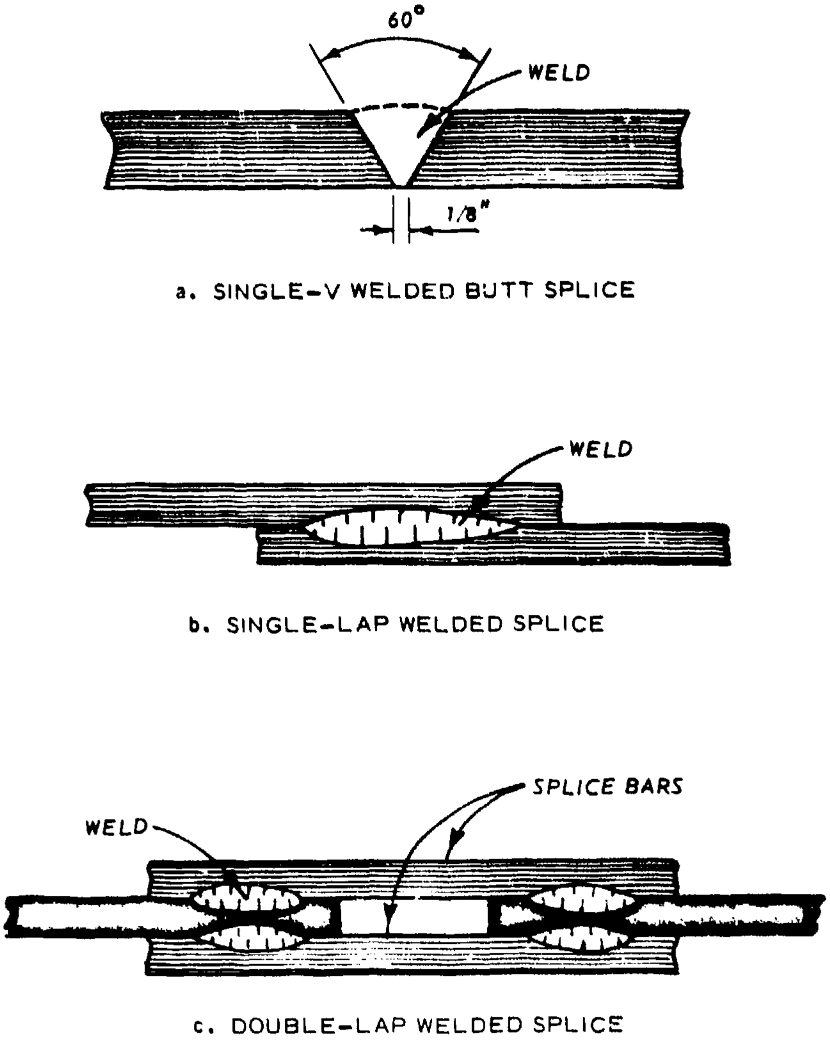


Figure 9. Example weld splices for reinforcing bars

(3/8-in. diameter) used on part of the South Dakota highway are inadequate as either load transfer or tie bars. This also is true of the Soviet practice of welding two points on a slab edge together. This connection joint may be useful as a construction expedient to maintain alignment of slabs but will not function under traffic for load transfer. It is possible to design a load-transferring welded joint using some variation of the Michigan, South Dakota, or Soviet designs. However, the bar size and spacing that will accomplish this objective must be selected from Table 9. This type of joint will require a large number of

field welds under awkward working conditions due to narrow dimensions around the joint. A 12-ft by 15-ft by 8-in.-thick slab with a single-lap welded splice for a joint similar to the one used in South Dakota highway would require 48 field welds of 1-in. bars for load transfer. A more satisfactory double-lap joint would require 192 welds, and the preferred butt splice would be very difficult to fabricate. Welded joint connections pose a number of problems and should probably be avoided if possible.

Grouted shear key

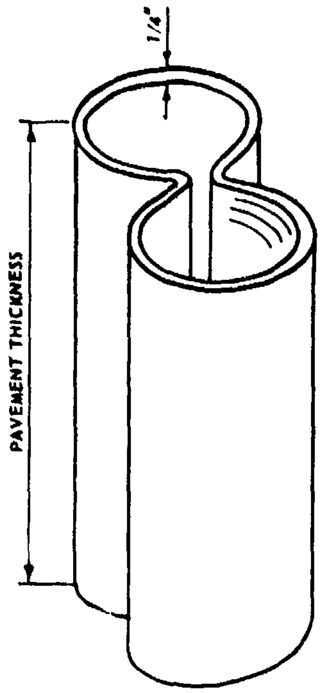
54. A grouted shear key such as shown in Figure 2b is relatively simple to fabricate and construct. The inclined faces of the key ensure mechanical interlock as well as adhesion of the grout to the slab face. Special epoxy and other related polymer grouts can obtain higher adhesion strengths, but a mechanical interlock would still be desirable. Expansive cements may also have an application and could cause some beneficial prestress in the slab. The grout keys used in the South Dakota pavement were subjected to 50 applications of a 7500-lb wheel load in the laboratory without causing distress (Hargett 1970). More testing is needed to evaluate grouted shear keys for large numbers of load repetitions and for heavy wheel loads such as for aircraft or container handling vehicles.

Key joint

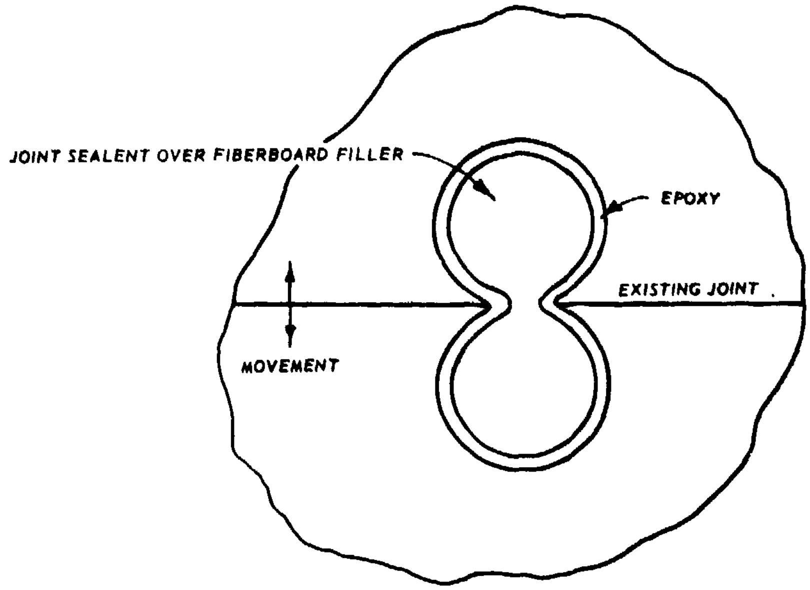
55. A key joint would be simple to form, but field assembly would be difficult. Any attempt to slide a slab horizontally will push material into the joint between the slabs. Consequently, one side of the slab must be lifted to allow the male end of the key to be inserted, and then the slab can be lowered onto the base. Some of the Soviet literature reported the use of tongue-and-grove joints, presumably the same as a key joint in United States terminology, but provided no details. The Corps of Engineers limits the use of keyed joints to pavements 9 in. or more in thickness and prohibits their use on pavement subject to channelized traffic on medium- and heavy-load airfields.

Compressible steel tube

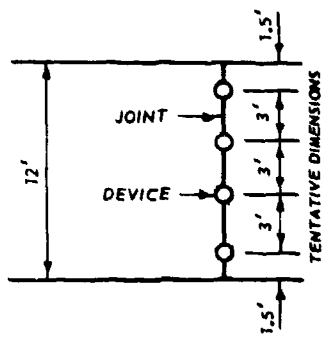
56. Figure 10 shows a joint load transfer device developed at the



a. Isometric view of device



b. Plan view



c. Proposed layout for highway

Figure 10. Deformable steel tube load transfer device (after Barenberg and Smith 1979)

Laboratoire Central des Ponts et Chaussees in France. This device consists of a steel deformed tube that must allow expansion and contraction within the elastic range of the steel, transfer load between slabs through shear, prevent relative displacement of slab surfaces, and allow the slab to expand without excessive restraint forces from the

steel. Barenberg and Smith (1979) describe an experimental installation of this device that successfully cuts deflections on an existing pavement by over half. The steel tube was compressed beyond its elastic range during the summer slab expansion, and the bond with the slab failed during slab contraction in the winter. Further research is being conducted with this joint device. If the research is successful, the device would be easy to place in preformed inserts in precast pavement slabs.

Other load transferring joints

57. Figure 11 illustrates potential concepts for other load transferring joints. In Figure 11a, a thin steel plate is inserted from the side between two slabs after they are placed. A grout is injected under pressure beneath the steel plate to force the plate into tight contact with the slabs.

58. In Figure 11b a tie or dowel bar is placed in a preformed recess of the slabs and grouted into place. If, as on a highway, traffic comes from only one direction, from right to left in Figure 11b, the inclined faces of the slab can transfer some load without the tie bar. The Japanese horn joint in Figure 3 could be used for slabs with vertical faces.

59. A sleeper slab can be placed under the joint as shown in Figure 11c. This effectively thickens the edge of the slab at the joint but requires excavation or special preparation of the subgrade to accommodate the sleeper slab. The precast slab could also be cast with a thickened edge, and the sleeper slab omitted. However, subgrade preparation for a variable-thickness slab would be very awkward in the field.

60. Figures 11d and e show a method of placing dowels or tie bars in recesses cast into the slab. If the dowel bar were cast in Slab 2, the dowel could easily be bent or damaged during storage and transportation. Dowels could be inserted into Slab 2 immediately before it is lowered into place. Once Slab 2 is in place, the recess in Slab 1 with the protruding dowel bar from Slab 2 is grouted. The faces of the recesses in Slab 1 should be inclined so that the grout key has mechanical interlock with the slab.

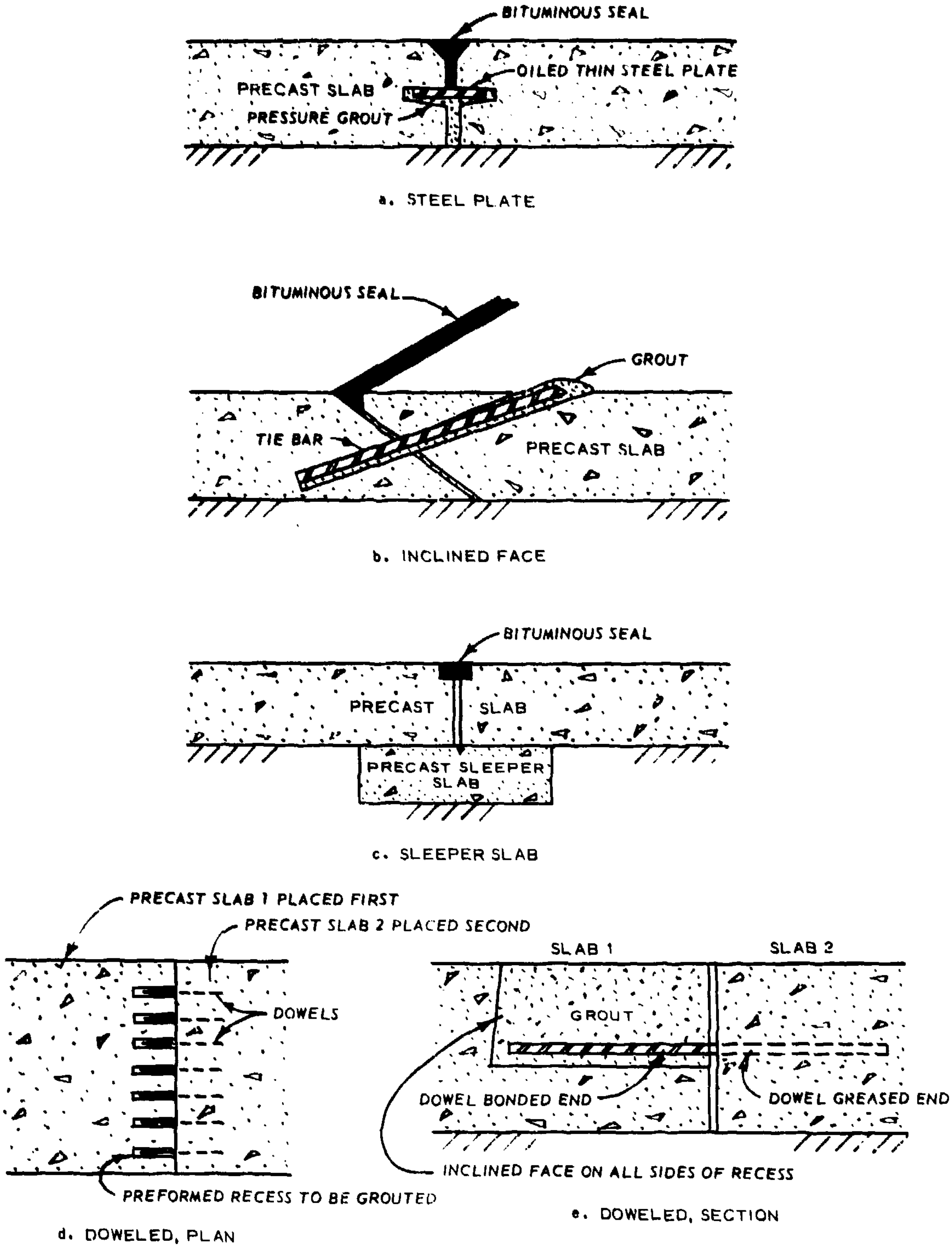


Figure 11. Load transferring joints for precast slabs

Expansion joints

61. Precast pavement joints must allow for concrete expansion and contraction from temperature changes and must be sealed to prevent debris from entering the joint. If one slab edge is sprayed with a bitumen to prevent the grout from bonding, joints such as those shown in Figures 11a or e allow contraction to occur. A compressible insert such as fiberboard placed in the joint or on the face of one slab allows expansion to occur in joints in Figures 11c or e. A joint such as the one shown in Figure 11b does not allow temperature movement. Either periodic expansion joints must be included or the joint is limited to uses such as a longitudinal joint on a highway where temperature movement can be ignored.

62. Figures 11a through c show three possible joint sealant concepts. The edges of the slab can be chamfered as the Hamburg slabs were (paragraph 21) to prevent spalling, and this can form the sealant reservoirs (Figure 11a). The thin, feathered upper edge of the slab in Figure 11b can be cut back to a vertical face to prevent spalling and breakup of the edge. This face would then form the sealant reservoir. A conventional rectangular reservoir as currently used could be easily included on almost any precast slab as shown in Figure 11c.

Slab separation

63. It is often necessary to provide restraint against slab separation under traffic even if the pavement design does not repair load transfer across the joints. For instance, a two-lane highway is designed for edge loading without load transfer because of loads on the outside edge of the pavement. However, the longitudinal joint will widen under traffic if there is no connection between the traffic lanes. Joint designs such as Figures 11b and d can meet this requirement. Smaller tie bars at greater spacing can be used instead of dowels. The bar in Figures 11d and e would have to be epoxied into Slab 2 to prevent separation of the slabs.

64. Another approach is illustrated in Figure 12a. Bars can be inserted through holes cast in the slab and nuts fastened on the end. The precast, prestressed taxiway at Melsbroek, Belgium (Vandepitte

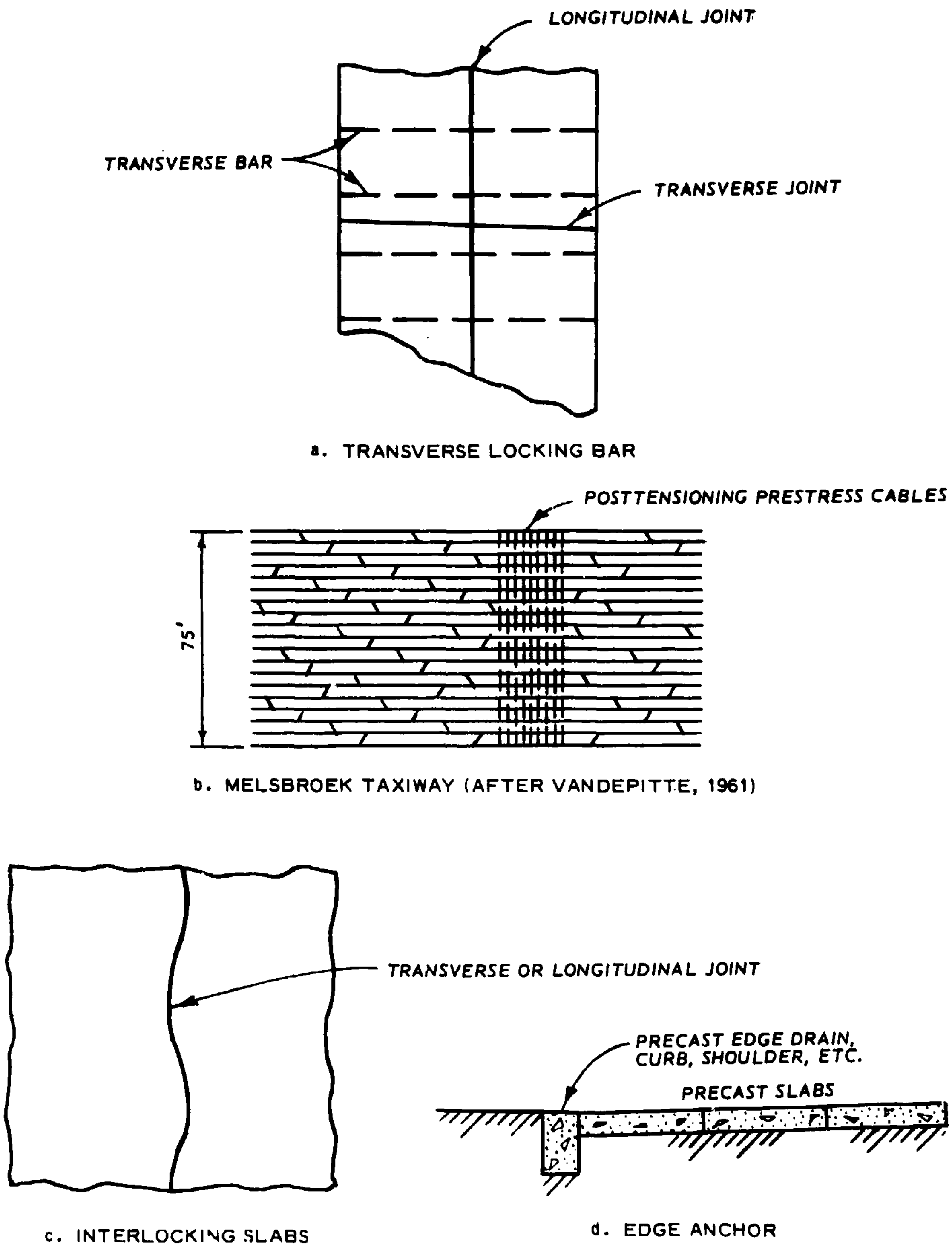


Figure 12. Maintaining slab alignment for precast pavements

1961), Figure 12b, illustrates an effective extension of this approach. The transverse joints are inclined so that the transverse, posttensioning cables cross both longitudinal and transverse joints. When the pavement is stressed, this method provides load transfer across both longitudinal and transverse joints and maintains the pavement integrity. Test loads up to 50 tons did not reveal any weakness or discontinuity in these joints. Slabs pretensioned longitudinally when cast and posttensioned across transverse and longitudinal joints in the field appear to be one of the most effective concepts for precast pavements.

65. If two slabs interlock as shown in Figure 12c, the slabs cannot move parallel to the joint. A highway constructed of slabs with a straight exterior edge and interlocking edges on the other three sides would be stable. Smooth curves as shown in Figure 12c can be built in a precasting plant and can avoid stress concentrations and cracking associated with perpendicular intersections.

66. Edge restraint can also prevent slab separation as shown in Figure 12d. This edge anchor can also include surface and subsurface drainage systems, curbs, or similar related structures.

Evaluation of Design and Construction Techniques

67. It is possible to design precast pavements by adapting current pavement design methods. Some questions remain on the effect of numerous joints on the Corps of Engineers prestressed pavement design assumptions, and further study of this area is needed. Handling stresses as well as traffic loadings must be considered in design. There are a number of possible joint designs to accomplish load transfer across joints, but testing would be needed to determine their effectiveness. The prestressed slab would appear to be the most effective precast unit for pavements since it uses the least amount of materials and results in thinner, lighter sections to be transported and handled.

68. Existing techniques of manufacture and transportation appear adequate to meet pavement requirements. These topics, as well as U. S Army uses for precasting, are covered in more detail by McDonald and Liu

(1978). Construction techniques will have to be developed but should not offer any insurmountable problems. A leveling course of sand, growth, or other material will be needed under the slab. The roughness of the final surface will largely be controlled by the final contour of the leveling course. This suggests that automatic subgrade profiling machines or other automated, precision leveling equipment will be needed. The Japanese leveling system shown in Figure 3 would probably be time-consuming and therefore expensive to use in the field. The slabs themselves can be lifted and placed with conventional cranes using any of a variety of possible pickup details on the slab. Vacuum lifters, which use a vacuum force to lift precast units, are available in the precast industry and do not require these pickup details. Different methods of seating the slabs in the leveling course have been tried previously, but further work to find an effective method would be necessary.

PART V: FEASIBILITY OF PRECAST PAVEMENTS

Cost

69. If precast construction is to be competitive with conventional construction, a market must exist for mass-produced, identical slabs. The costs of the manufacture of the precast slabs for the Brookings, South Dakota, highway as shown in Tables 2 and 3 exceeded conventional concrete paving costs by over a factor of 2. These figures do not include the additional costs of transportation, construction, and asphaltic concrete overlay. The unit cost of the precast slab can be reduced only by increasing the amount of production so that the efficiency of mass production becomes effective. A mile of 24-ft-wide highway contains 704 individual 12- by 15-ft slabs. A 96-ft-wide taxiway or runway would contain over 2800 slabs per mile of length.

70. Modern methods of concrete pavement construction with slipform pavers are highly automated and very efficient on large projects. Consequently, large projects that could generate sufficient market for precast units already have a very efficient conventional construction technique. Precasting may have more potential when there are numerous small- to moderate-sized projects concentrated in one area, as in an urban area. In this situation, demand may be high enough to reduce precasting manufacturing costs, but the small size of the projects prevents modern construction techniques from being as effective.

Casting and Assembly Tolerances

71. Casting and assembly tolerances for precast slabs must allow economical construction, but, at the same time, they must provide a smooth usable surface. Tables 10 and 11 show suggested casting and precast construction tolerances from Transportation Research Board (1974) and Vander Wal and Walker (1976) while Table 12 shows the smoothness requirements of the U. S. Army and Corps of Engineers (Department of the Army 1975; Office, Chief of Engineers, 1964).

72. Current suggested casting tolerances in Table 10 suggest that it will be exceedingly difficult to meet the smoothness requirements of Table 12 for roads, streets, runways, taxiways, and calibration hardstands. The acceptable 1/8-in. surface deviation from Transportation Research Board (1974) and the 1/4-in. warpage or the 1/4-in. surface deviation in a 10-ft bow (length/480) from Vander Wal and Walker (1976) are already at or exceeding the allowable limits for these pavements without any allowance for construction imperfections. Precast pavements cannot be built to meet current Corps of Engineers surface smoothness requirements for roads and airfield pavements.

73. The Soviet Union allows a maximum joint width of 0.6 in. and elevation difference of 0.2 in. between adjacent slabs (Gerberg and Osipon 1962), and the precast slabs used in European container handling terminals often had differences in elevation of 0.2 in. (Patterson 1976). These elevation differences exceed the 1/8 in. (0.125 in.) allowed for airfields and roads in Table 12.

Applications and Limitations

74. The roughness of precast pavements discourages their use in conventional roads and airfield pavements. The operation of modern high-performance military jet aircraft requires smooth landing surface. Military cargo aircraft such as the C-130, C-141, and C-5 have varying capability to operate on rough unsurfaced and semiprepared forward area airfields. Therefore, military cargo aircraft could presumably operate on precast pavements, but tactical fighter and stategic bomber aircraft probably could not. Because roughness controls the speed of vehicles on a road, precast pavements are of doubtful value for high-speed roads or highways. They may find application in urban areas, military posts, and similar locations where vehicle speed is limited. High cost and surface roughness presently make precast pavement a poor competitor with conventionally constructed concrete pavements for roads and airfields.

75. Storage areas, maintenance facilities, and parking areas offer the most promising conventional application for precast facilities.

Reduced vehicle speeds in these facilities reduce the importance of surface smoothness. The use of precasting becomes a question of economics, a disadvantage of precast pavements in the past.

76. Precast units can be placed in freezing and wet weather. This factor could provide distinct economic or military advantages and may make precasting a feasible alternative to conventional construction on some projects.

77. Precast units may be used advantageously where large subgrade settlements are expected. After settlement has occurred, the units may be mudjacked to a level position, or they may be removed while the subgrade is brought back to grade. Precast units have been found to be economical for container terminals in Europe when large subgrade settlements occur (Patterson 1976).

78. Precast units that are not permanently joined by grouting, welding, or other means can be recovered and reused. This may prove useful for repetitive construction of detours or temporary facilities while an existing pavement is being repaired or upgraded. Similarly, a facility that is being built in stages may need to move roadways or parking areas as the facility expands. By using precast units, the investment in pavement can be retained and reused.

79. Operations in a military theater are influenced by such factors as speed of construction and weather. Conventional construction criteria such as cost and roughness are less important in this environment. Precast pavements have potential for application here, but metal landing mats do also. Landing mats can be assembled rapidly by hand, are already type-classified, and are in the inventory. These mats are designed for rapid, expedient construction of temporary pavements with a minimum of support equipment. Typical uses would include construction of forward area airfields or rapid expansion of aircraft parking ramps at an existing airfield in the theater of operations. Precast concrete slabs would be more appropriate for semipermanent construction in the rear area of the theater of operations. Possible applications would include expansion of container handling facilities in a port, pavement construction or repair on the line of communications, or construction of

pavements for storage yards. In quantity, the medium-duty landing mat cost of $40.50 a square yard in 1968 compared with the Brookings, South Dakota, precast concrete cost of $18.67 (1968). Facilities must exist or be built in the theater of operations if precast concrete pavement slabs are to be used. The weight and volume of the slabs make it impractical to ship them to a theater of operations.

PART VI: CONCLUSIONS

80. Precast concrete does not appear to offer a net advantage for construction of conventional pavements at this time. Past experience indicates that it is more costly than conventionally constructed concrete pavements, and the final surface smoothness is distinctly inferior. Modern methods of concrete pavement construction are increasingly automated, and there appears to be little prospect of precasting being competitive in cost or smoothness for conventional pavement.

81. Precast pavements may find some limited application for such special problems as construction in adverse weather, subgrade settlement, temporary pavements that need to be relocated, and military operations where weather problems and speed of construction are important.

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Table 1

Standard Precast Slabs Produced in the Soviet Union

Slab	Dimensions, ft	Thickness in.	Weight tons	Reinforcement	lb Reinforcement/ft^2 of slab PS*	Plain**	Total
PAG-III	6.6 by 13.1	5.5	3.1	0.55-in.-diam Longitudinal PS* 0.20-in.-diam Transverse	1.27	1.16	2.43
PAG-IV	6.6 by 13.1	5.5	3.1	0.12-in.-diam Longitudinal PS 0.20-in.-diam Transverse	0.58	1.16	1.74
PAG-IX	10.5 by 19.7	5.5	7.4	0.12-in.-diam Longitudinal PS 0.12-in.-diam Transverse PS	1.01	0.08	1.09
PAG-XIV	6.6 by 19.7	5.5	4.6	0.55-in.-diam Longitudinal PS 0.20-in.-diam Transverse	1.32	1.05	2.37
PAG-XV	6.6 by 19.7	5.5	4.6	0.12-in.-diam Longitudinal PS 0.20-in.-diam Transverse	0.50	1.05	1.55
PAG-XV-1	6.4 by 19.2	5.5	4.4	0.12-in.-diam Longitudinal PS 0.20-in.-diam Transverse	0.62	1.11	1.73

Note: The PAG-IX slab is biaxially prestressed with a longitudinal prestress of 400 psi and a transverse prestress of 300 psi. The remaining slabs are prestressed only in the longitudinal direction. All slabs require a minimum grade 300 concrete (4270 psi).

* PS = Prestressed concrete.

** Unstressed concrete.

Table 2

Cost of Precast Construction at Brookings, South Dakota (Larson and Hang 1972)

Item	Cost/yd^2	Percent of Total Cost
Slab Manufacture	$13.62	73.0
Transportation	0.83	4.4
Unloading Slabs	0.29	1.6
Fine-Grading Subbase	0.24	1.3
Bedding Sand	0.45	2.4
Placing Slabs	0.62	3.3
Grouting Slabs	1.69	9.0
Asphaltic Concrete	0.93	5.0
Total	$18.67	100.0

Table 3

Relative Cost of Precast and Conventional Concrete Pavement (Larson and Hang 1972)

Location	Date	Type Pavement	Thickness in.	Relative Cost*
Brookings, South Dakota	1968	Precast	8	1.00
Brookings, South Dakota	1968	Precast	8	0.80**
South Dakota	1968	Plain	8	0.35
North Dakota	1966	Continuously reinforced	7	0.36
North Dakota	1967	Continuously reinforced	8	0.35
Wyoming	1968	Plain	8	0.30
Minnesota	1968	Reinforced	9	0.34
Iowa	1968	Plain	8	0.28
Iowa	1968	Reinforced	10	0.42
Iowa	1968	Continuously reinforced	8	0.39

* Cost per square yard divided by $18.67 per square yard (see Table 2).

** Estimated cost for Brookings project with improved procedures $15 per square yard.

Table 4

Summary of Precast Concrete Pavements

Slab	Dimensions ft by ft by in. Thickness	Length/Width Ratio	Type	Use
	Union of Soviet Socialist Republics			
PAG-III	6.6 × 13.1 × 5.5	2.0	Prestressed	Airfield
PAG-IV	6.6 × 13.1 × 5.5	2.0	Prestressed	Airfield
PAG-IX	10.5 × 19.7 × 5.5	1.9	Prestressed	Airfield
PAG-XIV	6.6 × 19.7 × 5.5	3.0	Prestressed	Airfield
PAG-XV	6.6 × 19.7 × 5.5	3.0	Prestressed	Airfield
PAG-XV-1	6.4 × 19.2 × 5.5	3.0	Prestressed	Airfield
Moscow (Mednikov et al. 1974)	Hexagon 3.8-ft side, 7.1-in. thickness	--	Plain and Reinforced	Road
(Glushkov and Rayev-Bogoslovskii 1970)	3.3 ft × 3.3 ft 3.8 ft × 4.9 ft	1.0-1.29	Plain	Road
(Glushkov and Rayev-Bogoslovskii 1970)	5.7 to 9.8 ft × 19.7 ft	2.0-3.5	Prestressed	Road
(Stepuro et al. 1964)	6.6 × 19.7 × 5.5	3.0	Prestressed	Road
(Smulka 1963)	6.6 ft × 19.5 ft	3.0	Prestressed	Road and Airfield
(Dubrovin et al. 1962)	9.9 ft × 19.8 ft	2.0	Reinforced	Road
(Birger and Klopovskii 1961)	8.2 × 11.6 × 6.4	1.4	Reinforced	Road
(Mikhovich et al. 1961)	4.9 × 5.7 × 6.7	1.2	Reinforced	Road

(Continued)

Table 4 (Concluded)

Slab	Dimensions ft by ft by in. Thickness	Length/Width Ratio	Type	Use
		Union of Soviet Socialist Republics (Continued)		
(Glushkov and Rayev-Bogoslovskii 1970)	Hexagon 4.9-ft side, 5.5-8.7-in. thick	--	Plain	Airfield (1940's)
(Glushkov and Rayev-Bogoslovskii 1970)	Hexagon 4.1-ft side, 3.9-5.5-in. thick	--	Plain	Airfield (1930's)
		United States		
(Mellinger 1956)	1 × 18 × 5.5	18	Prestressed	Missile
Michigan (Transportation Research Board 1974)	6 to 12 × 12 × 8 or 9	1.0-2.0	Reinforced	Road
Brookings, S. D. (Larson and Hang 1972)	6 × 24 × 4.5	4.0	Prestressed	Road (1968)
		Europe		
Hamburg (Patterson 1976)	6.6 × 6.6 × 5.5 8.2 × 8.2 × 5.5	1.0	Reinforced	Port (1968)
Melsbroek (Vandepitte 1961)	4.1 × 39 × 3	9.5	Prestressed	Airfield (1958)
Finningley (Hanna 1976)	9 × 30 × 6	3.3	Prestressed	Airfield (1956)
London (Stott 1955)	2.9 × 2.9 × 6.5	1.0	Prestressed	Airfield (1949)
Orly (Harris 1956)	3.3 × 3.3 × 6.3	1.0	Prestressed	Airfield (1947)
		Japan		
(Sato, Fukute, Inukai 1981)	7.5 × 32.8 × 7.9	4.4	Prestressed	Airfield

Table 5

Effect of Different Arrangements for Handling PAG-III and PAG-XIV Slabs

Slab	Length ft	Type Pickup	ℓ*, ft	Maximum M_n** ft-lb	Maximum M_p† ft-lb	Percent of Maximum Moment
PAG-XIV	19.7	End	0	0	11,330	100.0
		1/4 and 3/4 points	4.92	2830	0	25.0
		Balanced moment††	4.08	1940	1,940	17.1
PAG-III	13.1	End	0	0	5,080	44.8
		1/4 and 3/4 points	3.27	1270	0	11.2
		Balanced moment††	2.71	870	870	7.7

Note: Both slabs are 6.6 ft wide. Slab PAG-III weighs 3.1 tons and slab PAG-XIV weighs 4.6 tons.

* ℓ denotes distance of pickup point from end of slab.

** M_n denotes negative moment (tension in top).

† M_p denotes positive moment (tension in bottom).

†† $M_n = M_p$ for balanced moment.

Table 6

Loadings for Sample Designs*

Vehicle	Gross Load lb	Wheel Load lb	Tire Contact Area $in.^2$	Tire Pressure psi	Remarks
C-141	320,000	37,400	208	180	Twin-tandem main gear
F-15	51,000	23,000	90	260	Tricycle gear
18-kip axle	18,000	4,500	50	90	Dual wheels at 17-in. spacing
Hyster 620B	144,310	33,410	257	130	Dual wheels at 20-in. spacing

* See Table 7 for pavement thicknesses of sample designs.

Table 7

Sample Pavement Design Thicknesses

			Pavement Thickness, in.				
				Reinforced			
Vehicle	Load Transfer	No. of Passes	Plain	$S_r = 0.15$*	$S_r = 0.5$*	Fiber-Reinforced	Prestressed**
C-141	Yes	25,000	12-1/2	10-1/2	8-3/4	8-1/2†	7 (410)
	No		16-1/4	13-1/2	11-1/2	11-1/4	9-1/2 (399)
F-15	Yes	50,000	9-1/4	7-3/4	6-1/2	5-1/2	4 (356)
	No		10-3/4	9	7-1/2	6	5-1/2 (372)
18-kip axle	No	250,000	8	6-3/4	5-3/4	5-1/4	4†† (100)
Hyster 620B	Yes	1,000	11-1/4	9-1/2	8	6-1/4	5 (364)
	No		13-3/4	11-1/2	9-3/4	7-1/2	7 (306)

Note: Subgrade modulus $k = 200$ pci for all designs.
* S_r = percent reinforcing steel.
** Numbers in parentheses are design prestress levels in pounds per square inch. Subgrade restraint and temperature warping stress assumed to be 55 psi.
† Controlled by deflection limits.
†† Considered minimum thickness to provide cover for steel.

Table 8

C-141 Sample Design Slab Weights

Type of Precast Slab	Concrete Weight, tons	Steel Weight, lb	Total, tons	Percent Weight Reduction*
Plain concrete	14.1	0	14.1	0
Reinforced, $S_r = 0.15$	11.8	101	11.9	15.6
Reinforced, $S_r = 0.50$	9.8	235	9.9	29.8
Fiber - reinforced	9.6	765	10.0	29.1
Prestressed	7.9	87.9	7.9	43.9

Note: Assumptions to calculate weights: slab size 12 by 15 ft, unit weight concrete 150 pcf, unit weight steel 490 pcf, prestress steel 240,000-psi yield strength, fiber reinforcing 6 lb per cubic foot of slab volume.

* Plain concrete slab weight used as base.

Table 9

Corps of Engineers Requirements for Dowel and Tie Bars

Application	Type	Pavement Thickness, in.	Bar Diameter, in.	Spacing, in.
Roads	Dowel	Less than 8	3/4	12*
		8 to 11**	1	13*
		12 to 15**	1-1/4	15*
	Tie	Any	5/8	30
Airfields	Dowel	Less than 8	3/4	12
		8 to 11.5**	1	12
		12 to 15.5**	1 to 1-1/4	15
		16 to 20.5	1 to 1-1/2	18
		21 to 25.5	2	18
		over 26	3	18
	Tie	Any	5/8	30

* For construction joints in conventional pavement that would be similar to precast pavement joints.

** Design to nearest inch for roads and nearest 1/2 in. for airfields, hence no intermediate values for 11 to 12, 11.5 to 12, etc.

Table 10

Suggested Casting Tolerances

Measurement	Flat Wall Panel*	Repair Slabs**
Length and width	±1/8 in. ≤ 10 ft +1/8 to -3/16 in., 10 to 20 ft +1/8 to -1/4 in., 20 to 30 ft ±1/4 in. > 30 ft	±1/4 in.
Thickness	±1/4 to -1/8 in.	±1/8 in.
Deviation of edge from straight line	1/16 in. per 10 ft 1/4-in. maximum	--
Squareness	1/4-in. difference in diagonals	±1/2-in. length of sides
Warpage (one corner out of plane)	1/4 in.	--
Surface deviation	Length of bow/480 (1/4 in. in 10-ft bow)	±1/8 in. in 10 ft

* Vander Wal and Walker 1976.

** Transportation Research Board 1974. Michigan slabs, length = 6, 8, 10, and 12 ft; width = 11 ft 11-1/2 in.; thickness = 8 and 9 in.

Table 11

Suggested Construction Tolerances for Precast Flat Wall Panels (Vander Wal and Walker 1976)

Measurement	Tolerance
Variation in plan	±1/2 in.
Deviation in plan from straight line	1/40 in. per foot; 1/2 in. in any 20 ft
Deviation in elevation from grade line	1/40 in. per foot; 1/2 in. in any 20 ft
Jog in alignment of matching edges	1/4 in.
Variation from specified joint width	±1/4 in.

Table 12

Surface Smoothness Requirements (from Department of the Army 1975; Office, Chief of Engineers 1964)

Pavement	Maximum Allowable Deviation
Roads and streets	1/8 in. in 10 ft
Other vehicular pavements (parking, storage, etc)	1/4 in. in 10 ft
Airfields and heliports	1/8 in. abrupt change
Runways and taxiways	1/8 in. in 12-ft long. 3/16 in. in 12-ft trans.
Runways and taxiways with cross slopes over 1 percent	1/8 in. in 12-ft long. 1/4 in. in 12-ft trans.
Calibration hardstands	1/8 in. in 12-ft long. and trans.
Maintenance and parking	3/16 in. in 12-ft long. and trans.
Maintenance and parking with grades over 1 percent any direction	1/4 in. in 12-ft long. and trans.

Note: long. = longitudinal direction; trans = tranverse direction.

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